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COMMITTEE V.7

STRUCTURAL LONGEVITY

COMMITTEE MANDATE

Concern for the structural longevity of ship, offshore and other marine structures. This shall include diagnosis and prognosis of structural health, prevention of structural failures such as corrosion and fatigue, and structural rehabilitation. The focus shall be on methodologies translating monitoring data into operational and life-cycle management advice. The research and development in passive, latent and active systems including their sensors and actuators shall be addressed.

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1. DISCUSSION

1.1 Official Discussion by Dan M. Frangopol

1.1.1 Introduction

I would like to congratulate the authors for providing this comprehensive state-of-the-art report on structural longevity of ship, offshore and other marine structures. The report presents a timely update on specific aspects of structural longevity of marine structures with emphasis on life-cycle management methodologies and inspection and monitoring techniques. In particular, the report highlights two major challenges: integration and application. Although a broad spectrum of topics has been covered in the report, I would like to provide some remarks and comments revolving around the emerging life-cycle management methodologies including adaptive risk-based inspection planning, consideration of lifetime extension in life-cycle management, use of digital twin in life-cycle management, new inspection/monitoring/repair techniques, and incorporation of noneconomic factors in decision-making.

1.1.2 Adaptive risk-based inspection (ARBI) planning

As noted by the authors, rational life-cycle assessment and management should involve the planning of inspection/monitoring and the associated repair/rehabilitation actions based on the available data. For this purpose, risk-based inspection (RBI) planning plays an important role in the life-cycle management of deteriorating structures and is deemed a more powerful tool than prescriptive inspection plans. As a result, RBI has been used in both ship and offshore structures to improve structural longevity under corrosion- and fatigue-induced deterioration (Straub et al. 2006; Dong & Frangopol 2015b; Soliman et al. 2016).

Ideally, as mentioned in the report, inspection and the subsequent repair decisions should be adaptive and data-driven, indicating that the following decisions should consider the current condition of the structure, the historical inspection results, and the previous repair actions. Consider for example a fatigue-sensitive detail with a design service life of 20 years and a critical fatigue size of 30 mm. If the inspected crack size at year 3 is 10 mm, it is nearly certain that this detail cannot be used for the remaining design service life and should be repaired; the same crack size measured at year 18, on the other hand, may support the use of the detail until the end of the design service life.

Built upon the concept of RBI, recent efforts have been taken to achieve adaptive risk-based inspection (ARBI) (e.g. Nechval et al. 2009; Soliman & Frangopol 2014; Yang & Frangopol 2017; Yang & Frangopol 2018). Yang & Frangopol (2018) proposed an inspection/repair planning method for fatigue-critical details using dynamic Bayesian network (DBN) for updating and multi-objective optimization for decision-making. Similar to conventional RBI, the method is able to compare different inspection schedules and select the optimal solution based on different objectives. In addition, upon each inspection, the proposed method capitalizes on the information from the previous inspection/repair decisions to make an informed decision on the next intervention action. An example of ARBI can be found in Soliman & Frangopol (2014) where a comprehensive framework for life-cycle management of fatigue-sensitive structures has been developed. An adaptive inspection planning process in service of fatigued aircraft structures, with potential application to marine structures, is provided in Nechval et al. (2009). In their approach, planning in-service inspections is an adaptive control process, in which adaptation is performed by "self-modification and self-adjustment in accordance with varying conditions and environment." Therefore, the process of adaptive control of inspection of fatigue critical details attempts to reevaluate itself in the light of uncertainties in service as they unfold and change (Nechval et al. 2009).

ARBI enables the integration of historical and current conditions of structures in the life-cycle management. This is particularly important for the decision-making on lifetime extension and on the operational and maintenance plans during the extended life.

Therefore, in my opinion, ARBI deserves future attention.

1.1.3 Consideration of lifetime extension in life-cycle management

As mentioned in the report, many assets are approaching or have already exceeded their original design life. Therefore, lifetime extension is an extremely important issue of marine structures. The aforementioned ARBI can provide updated prediction regarding structural deterioration. Based on this updated information, lifetime extension can be considered for a preassigned extended service life, e.g. another 20 years of service. In this case, existing methods for life-cycle management can be directly applied to plan inspection/monitoring and maintenance actions. This situation is especially relevant to those assets that have already reached the end of their service life, and inspection/monitoring and maintenance plans in the extended lifetime are needed imminently in order to continue their service.

Alternatively, the extended service life can be treated as an objective in a multi-objective optimization framework. Since maintenance actions are able to extend the service life, rational planning of these actions can maximize the extended service life. This approach was originally proposed for deteriorating civil infrastructure (Kim et al. 2011) but has been successfully extended to marine structures in recent studies (Kim et al. 2013; Soliman et al. 2016). Compared to the approach of preassigning an extended service life, this approach is especially suited for assets that have not reached their design service life but are scheduled to have a longer service life (Liu & Frangopol 2018). For instance, Kim et al. (2013) adopted bi-objective optimization to plan inspection/repair actions of ship hull structures, simultaneously minimizing life-cycle cost and maximizing the extended service life. Soliman et al. (2016) further added the objective of minimizing expected maintenance delay, forming a tri-objective optimization problem. To handle the increasing number of objectives in the life-cycle management, efficient algorithms have been developed to overcome the computational difficulties (Kim & Frangopol 2017; Kim & Frangopol 2018a; Kim & Frangopol 2018b).

1.1.4 Use of digital twin in life-cycle management

Many existing studies on structural longevity, including those mentioned in the report, are generally focused on the structural detail or structural member level. In order to promote the application of these approaches, extension to structural system level is urgently needed. One option to achieve this goal, as mentioned in the report, is to create digital twins of structures and to take advantage of the ever-evolving sensing technology. Digital twin and global monitoring can help (a) identify critical structural details and members as well as (b) create system models of whole structures based on detail and member performance.

Despite the benefit brought by the creation of digital twin, its direct use in life-cycle management of marine structures still faces many challenges, mainly from the computational point of view. A main objective of creating the digital twin of a structure is to replicate the structural and operational performance as accurate and comprehensive as possible. This implies a computational barrier for directly using digital twin in tasks like inspection/repair planning. The report recognizes the benefits of creating digital twins but neglects, to some extent, the gap between the complexity of digital twins and the life-cycle management practices. A potential method to fill in this gap is to use digital twin to build computationally efficient surrogates for different life-cycle management objectives (e.g. Mondoro et al. 2016; Gaspar et al. 2017). Many techniques in artificial intelligence and machine learning (e.g. artificial neutral network and kriging models) can be used for this purpose. It is suggested that the future report should include progress in filling the gap between the complexity of digital twins and the life-cycle management practices.

1.1.5 New inspection, monitoring, and repair techniques

Another challenge of applying ARBI is to incorporate new inspection/monitoring techniques in the planning. Although many new techniques have been developed, as documented in the ISSC2015 and the current report, the information needed for applying life-cycle management methods is still incomplete. For instance, an inspection technique needs to provide the values of the probability of detection (PoD) and probability of sizing (PoS) in order to be used in the framework of RBI planning. However, this information is not always available for new techniques. It is therefore recommended that standardized guidelines be provided for the development of new inspection/monitoring techniques. In these guidelines, the specification of PoD and PoS should become an indispensable requirement for the completeness of a new technique. On the other hand, for new techniques already having this information, dissemination of these techniques among researchers, officials, and practitioners in structural integrity management (SIM) is also extremely important.

Similar to inspection/monitoring techniques, RBI planning requires detailed knowledge (especially in probabilistic terms) of the time-dependent effects of repair actions on the structural performance. Nevertheless, probabilistic analysis of the effects of various repair actions on time-dependent structural performance is still rare. Much effort should be taken in order to ultimately integrate inspection, monitoring and repair techniques into a probabilistic life-cycle management framework.

1.1.6 Incorporation of noneconomic factors in decision-making

Finally, I would like to draw attention on the consideration of noneconomic factors in the decision-making process regarding SIM for structural longevity. The report, despite being very comprehensive, is mainly focused on the economic aspect of structural longevity, i.e. minimization of capital and operational expenses. Social and environmental effects on decision-making should also be properly considered. For instance, in the risk assessment of ship collision, Dong & Frangopol (2015a) considered social and environmental consequences including fatalities, injuries, and oil spilling. In general, incorporation of noneconomic factors indicates that the decision-making regarding structural longevity should be sustainability-informed instead of being solely cost-driven.

It should be noted that a sustainability-informed decision-making process usually delivers a different result from that based on conventional economic indicators (Frangopol & Soliman 2016; Frangopol et al. 2017). This is partly attributed to the fact that social and environmental consequences are difficult to monetize and are subject to different appreciation/depreciation rates compared to that of economic expenses. In order to consider the economic, social and environmental aspects of structural longevity, multi-attribute utility theory has been used in the life-cycle assessment and management of marine structures (Dong & Frangopol 2015a; Dong et al. 2016). This theory can consider the three aspects of structural longevity and the risk attitudes of decision makers.

A major challenge for incorporating noneconomic factors using multi-attribute utility theory is to characterize institutional risk attitudes regarding the design, operation, and maintenance of marine structures. This includes the calibration of weighting factors for different attributes (i.e. economic, social, and environmental) as well as the quantification of risk perceptions with respect to different attribute values. Overall, I would like to suggest more discussions on sustainability-informed decision making in life-cycle management of marine structures.

1.1.7 Summary and recommendations

The discussion herein has highlighted challenges and future directions for improving structural longevity of ship, offshore and other marine structures. These include the use of adaptive risk-based inspection planning, consideration of lifetime extension in life-cycle management, accurate and efficient surrogate models of digital twins, longevity-informed specifications for new inspection/monitoring/repair techniques, and incorporation of noneconomic factors in decision-making. It is recommended that these aspects be considered in the next committee meeting and its report.

1.1.8 Acknowledgements

The discusser is grateful to Dr. David Y. Yang for constructive suggestions and acknowledges the financial support of the U.S. Office of Naval Research during the past 10 years. This support provided a fertile ground for research and innovative developments in the field of life-cycle of marine structures and their optimum management under uncertainty.

1.2 Floor and Written Discussions

1.2.1 Lotfollah Pahlavan

Thank you very much. My question is about the idea of having a prediction model that can be fed with sensor or inspection data for more accurate prediction of structural longevity. According to my point of view a part of the problem originates from the data itself. This relates to the accuracy and reliability of your methods for acquiring the data, which you also correctly mentioned. So, should we not think of more holistic approaches, in which we already consider different aspects of the problem, such as damage, response, sensor data, and measurement uncertainty in an integrated framework, to better address the objective?

In addition to this, looking at the operational condition of structural assets in the offshore and maritime domain, there are always large variations in the environmental conditions. All of these variations may change the response of a sensor over the lifetime. For comparable applications in other sectors, there has been a focus on the development of so-called baseline-free methods, in which influences of environmental conditions and sensor coupling degradation are taken into account. Did the committee also encounter such research for maritime and offshore application?

1.2.2 Martijn Hoogeland

I appreciated the report of the committee on structural longevity. It covers a good portion of the issues related to longevity. I do have a few questions and remarks, though.

It is noted that corrosion is seen as a major driver for longevity. I agree on that observation. With respect to the corrosion measurements, the committee has missed the work done for coating condition monitoring. A patent of Thomas (2005) and a paper by Hoogeland et al (2016) showed a simple system that can continuously verify the isolation capacity of a coating system in a ballast tank. With regards to monitoring corrosion development, I wonder what systems have been identified that can effectively monitor a ballast tank or similar.

Risk-based inspections are developed in various industry fields, as well as in the maritime field. SAFEPEC and INCASSS are mentioned as EU projects that addressed the risk of a ship in terms of probability of not fulfilling hull girder strength criteria. I agree that practical application is lacking. What is the suggestion of the committee to have the owner or operators involved in the monitoring and prediction programs? How could owners or operators and the associated regulatory bodies be motivated to take the (perceived) benefits of condition based maintenance and risk based inspections?

Section 5 of the report mentions various systems that may lead to an efficient monitoring system, such as fibre optics and inverse FEM (iFEM). Are there applications known on real assets to show that the promises can be realized? Especially for iFEM it would be interesting to see a practical proof of principle.

Tools to perform remote inspections are developed in various projects, where HITS project is specifically mentioned. The global visual inspection of a cargo tank of an AFRAMAX tanker can be done with a camera on a stick, enabling views at bracket toes, while the operator remains on deck. It is advised that the next committee extends more attention to these kinds of developments.

1.2.3 George Wang

Thank you for the interesting coverage of the topic. I have two questions. The first, we see that risk-based inspection approaches are widely accepted in the offshore industry. However, we do not see much of this being applied in commercial shipping or in the navy. Could the committee share their perspective on this?

My second question is on the reliability of reliability analysis. I have had the opportunity to work on a dozen or so FPSO RBI projects. There I saw resistance from people. One of the reasons for this resistance was not the level of confidence in the reliability approach, but the level of confidence regarding the results. For instance, you could perform Bayesian updating, and the results might suggest that you should inspect, then, if nothing is detected, the interval to the next inspection becomes larger, even though the structure degrades further. We have seen cases like this, and these make people question whether the input to the probability model is good or not. Does the committee have any insights on this?

1.2.4 Torgeir Moan

I would like to start by commenting on RBI, so-called risk-based inspection. What we are using, and have been using for more than 20 years for offshore structures in Norway, we call it RBI, but it is, in fact, reliability based inspection planning, because our analysis is based on normal uncertainties inherent in loads, resistance and the quality of inspection, and so on. What we do not account for directly is human errors even though in-service experiences show that they do affect the fatigue life of structures. Due to fabrication errors, i.e. due to wet electrodes etc, crack defects, misalignment of plates etc might be larger than normal tolerances. This fact has two implications: 1) Inspections are crucial for assessing possible abnormal defects and imperfections; 2) this information shall be used to repair cracks and the true geometry should be used in reliability based inspection planning.

My second comment is on monitoring versus inspection. The main issues relate to the quality and cost of such approaches to ensure safety. For various reasons monitoring would be a preferred approach given that the quality is adequate. In our laboratory we have tested large scale structures to check the quality of acoustic emission and vibration measurements to detect cracks. Concerning the latter even under laboratory conditions the background noise disturbed the crack monitoring so much that we definitely have no chance of using this technique in-service. We have also looked at vibration measurements of jacket structures and found that vibration measurements based on changes in natural frequencies or modes was not feasible, because such dynamic properties depend on stiffness which is not sufficiently sensitive to small cracks.

I do not know about any case, at least not for an offshore structure in Norway, where instrumented monitoring is used to detect cracks, which is the damage of main concern, in load carrying structures. Another matter is of course is the use of monitoring to determine the dynamic response (preferably nominal and not hot spot stresses) for checking the inherent uncertainty in numerical methods for response analysis. The challenge in this connection is to have sufficient information about the loads imposed by the environment to have a realistic validation.

The important issue in connection with utilizing the inspection and monitoring, is robustness. By robustness, I mean reserve capacity in a structure with damage, and not redundancy in terms of counting of intact and failed components. Reserve capacity is needed so that you can tolerate the presence of cracks which are large enough to be detected by visual inspection (or NDE methods) or monitoring. Visual inspection still is the principal strategy in the offshore industry. In addition, the leak before break criterion is applied especially as a last safety barrier. For instance cracks in shuttle tankers operating in the North Sea were detected by the crew noticing oil spills on the sea surface adjacent to the tanker. Leak of water in or oil out or even loss of pressure amplified by introduced overpressure, is a very effective monitoring tool, contingent upon sufficient damage tolerance or robustness – which is a key structural property to rely on inspection or monitoring to enhance safety.

1.2.5 Mirek Kaminski

If I may reply to Prof. Moan, I share his thoughts. However, I see new developments that give hope. Mathematicians and measurement system suppliers do not sit still, but instead are working to improve systems and procedures. Large amounts of data are easier to collect and process. In Delft we are currently doing some research, which is showing hopeful results. We cannot guarantee it, but maybe in ten years' time, people will say that Prof. Moan was not right ten years ago.

1.2.6 Enrico Rizzuto

I have two comments and one question. The first comment relates to the application of this overarching concept of sustainability that was mentioned by Prof. Frangopol. In particular the risk for humans was a subject of a past ISSC report by committee IV.1: Design Principles and Criteria.

The other comment relates to the impact of risk, specifically for ships. I think that in evaluating impact we should consider the differences between platforms and ships since this impact of risk also depends on the amount and type of plants in the structure. So in a sense it is about more than the structure. For example, assume we have a perfect structure, and it is very well maintained. In this case the structure is very efficient, but in addition to this we have an engine in this structure, and the engine is worn out. Then this changes the way in which the lifetime extension is to be considered. With respect to this consideration there are differences between ships and platforms, because the plants in platforms are typically more accessible and easier to remove, and replace, than those of ships.

Finally, arriving at the question. Is it possible to establish some kind of definition of longevity? I would appreciate it, if there was some kind of definition in line with the graphs of failure life that have been shown by Prof. Frangopol. Could a simple quantitative measure be defined, such as the actual life divided by the design life, or is a more sophisticated approach needed?

1.2.7 Alysson Mondoro

I would like to thank the committee, the chairman and the official discusser for giving great presentations on this work. In my opinion you did a great job in covering the impact of life cycle costs on the overall costs of a structure, and it is important that this is considered in an early design stage. Could you comment on how this is currently used in the navy or in the industry, and whether or not you see any potential challenges or limitations with respect to this?

1.2.8 Petar Georgiev

In your presentation you mentioned that classification societies have guidelines for monitoring systems. Did you find any statistics on how many of such systems have been installed onboard?

1.2.9 Hyunkyoung Shin

In Korea, there are several projects for building floating offshore wind farms. Recently I have had the chance to talk with fishermen who want the floaters of the wind turbines to be artificial reefs, in order for these structures to create a symbiosis with marine life. So now I have to think about fouling, not anti-fouling. What would the effect of fouling be on the longevity of such an offshore structure? Or more generally, how do we consider the effect of fouling on the longevity of an offshore structure in the early design stage?

1.2.10 Gaute Storhaug

Regarding the number of ships that have been instrumented with monitoring systems, it is in the order of 700 to 800 vessels world wide. This would be between 0.5 and 1.0 percent of all ships, depending on how the fleet is defined.

Besides this, the question has been raised on the value of having a monitoring system in relation to longevity or lifetime extension, and the cost of such a system versus the value you get in return. My question is, has the committee, in their literature research, found any information on when a monitoring system should be installed to obtain the best value? Should you instrument the vessel when you want to make a decision on an envisioned lifetime extension, or should the vessel be instrumented from day one?

2. REPLY BY COMMITTEE

2.1 Reply to the Official Discusser Professor Dan M. Frangopol

The thoughtful review of our report by Prof. Frangopol is greatly appreciated by the committee and his valuable contributions add to the longevity dialogue that this committee has fostered amongst the ISSC community.

We agree with him that a new perspective is needed for long-term sustainment of marine assets. Owners and operators will need to have a sufficient business case for going beyond a reactive rule-based approach to maintenance and the adoption of a forward-thinking predictive approach. We agree with his comments and observations regarding limited application of structural reliability approaches. Although ship structural reliability technology has been steadily developed over the last several decades, real-world applications of it have been few, even where that approach could have a great benefit, such as planning for maintenance. There certainly is a need for time-based structural reliability, economic analysis of failure consequences, and cost effective mitigation strategies. The use of a risk-based perspective to support sustainment can have great value because risk and total ownership cost considerations provide a framework for evaluation the cost-benefit of risk mitigation strategies.

Although a broad spectrum of topics has been covered in the report, we would like to provide some remarks and comments revolving around the emerging life-cycle management methodologies including adaptive risk-based inspection planning, consideration of lifetime extension in life-cycle management, use of digital twin in life-cycle management, new inspection/monitoring/repair techniques, and incorporation of noneconomic factors in decision-making.

2.1.1 Adaptive risk-based inspection (ARBI) planning

The committee agrees that Risk-Based Inspection (RBI) methods should allow for the dynamic nature of lifecycle analysis and not be locked into use of as-designed or otherwise static data. Risk-based inspection methods described in the report do not preclude use of information as it becomes available (e.g. repairs, sensed or inspection data). A specific example of how RBI is considered inherently adaptive was noted in the report through an example provided by Chen et al. (2011) which uses detected crack size as an important parameter in an

RBI approach based on Bayesian updating. The committee agrees that more emphasis should be placed on the adaptive nature of RBI to avoid implying that the data and information used are not being updated and to ensure future developments are adaptive in nature. The committee agrees that application of adaptive risk-based inspection seems to have a significant potential. This approach is completely in line with the Bayesian framework when combining initial assumptions with actual observations. This is also outlined in Zhu & Frangopol (2013) which is referenced in the report. Use of dynamic Bayesian networks (DBN) as mentioned by the discusser will be particularly useful for increasing the computational efficiency associated with the statistical updating process. The additional references provided by Prof. Frangopol on adaptive RBI are greatly appreciated.

2.1.2 Consideration of lifetime extension in life-cycle management

Information about these additional references is highly welcomed by the committee. The topic of optimization in relation to lifetime extension has been discussed in the report, and reference to the paper by Soliman et. al. (2016) has been made. The computational challenges associated with an increasing number of objectives are substantial and should continuously be addressed by the present committee. It should be noted that techniques such as cloud computing will allow for processing large models incorporating large amount of data. However, it is foreseen that the most recent references provided by the discusser will be followed by comprehensive research activities such that implementation as part of procedures applied by the industry can be achieved.

2.1.3 Use of digital twin in life-cycle management

The committee is grateful that the discusser raises this very important issue. In the committee report, the possibility of improving computation time has been briefly discussed in connection with application of reduced order models. The role of inverse finite element methods (iFEM) has also been briefly touched upon. It is very important that such models are able to represent the essential characteristics of the physical structure with sufficient accuracy. Furthermore, as pointed out by the discusser it is crucial that life-cycle management objectives are taken properly into account whenever surrogate models are applied.

2.1.4 New inspection, monitoring, and repair techniques

The discusser focuses on a very important aspect with respect to new inspection, monitoring and repair techniques. Whenever such new methods are introduced it usually takes some time and experience before their properties (i.e. in terms of strong as well as weak sides) can be adequately assessed. Development and testing of such methods are usually first performed under well-controlled laboratory conditions. The statistical/probabilistic description based on such testing is rarely adequate in order to reflect those associated with full-scale conditions. Hence, development of accurate and refined probabilistic representations of their "model uncertainties" will frequently be a slow and cumulative activity. This can also be the reason that the industry in general is somewhat hesitant to choose such new techniques unless no established alternative exists. Accordingly, it may be reasonable to start with a "pessimistic" statistical representation of new techniques until they have proven otherwise.

Furthermore, this comment by the discusser underlines the importance of the following observation which was made in the report: "The lack of acceptance of probabilistic methods for the assessment of aging may be assigned to the complexity and computational effort concerned with the approach, and the long absence of research into practical applications".

2.1.5 Incorporation of noneconomic factors in decision-making

As pointed out by the discusser, consideration of noneconomic factors represents a basic challenge. This has been addressed by the committee report in reviewing the work by Dong et al. (2016) and Frangopol and Soliman (2016).

The weighting factors pertaining to noneconomic types of attributes may vary significantly from one stakeholder to the next. An implicit way of avoiding events with severe consequences is by introducing a maximum value of the associated failure probability that can be accepted, thereby limiting the corresponding risk level. This acceptable probability can in turn be related to the so-called Life-quality Index (LQI) as outlined in Pandey and Nathwani (1997) and Lind, (2002). This index represents a possible measure that may be able to balance the different economic and non-economic aspects in a more objective manner. This is clearly an item that should be addressed in some more detail as part of future work by this committee.

2.1.6 Summary and recommendations

The discussion herein has highlighted challenges and future directions for improving structural longevity of ship, offshore and other marine structures. These include the use of adaptive risk-based inspection planning, consideration of lifetime extension in life-cycle management, accurate and efficient surrogate models of digital twins, longevity-informed specifications for new inspection/monitoring/repair techniques and incorporation of noneconomic factors in decision-making. It is recommended that these aspects be considered in the next committee meeting and its report. Again, we thank Prof. Frangopol for his thoughtful comments, and look forward to the work of the Structural Longevity committee for ISSC 2021.

2.2 Reply to Written and Floor Discussion

2.2.1 Reply to Lotfollah Pahlavan

The committee agrees with the idea of considering data collection in a broader aspect. The challenges start with assuring that the uncertainty associated with the sensor is acceptable, that the uncertainty of how you get the data from the sensor to your model is acceptable, determining that the process works, how the problem is formulated, and what objective you are after. All these are necessary for you to know that you are collecting the right data. The tighter you can couple these aspects the better, but you definitely cannot lose sight of the importance of why you are collecting the data and how your model is going to use it. Just taking a number and feeding it in is not very efficient.

As for what are described as baseline-free methods for accounting for degradation, the committee did not find any references to their use in marine structures. That is an area that the committee for 2021 can investigate. Sensor degradation and variation based on environmental conditions is very important. Sensors must be robust and able to perform reliably in the range of conditions that they are going to experience. We are concerned with the use of pressure tabs to measure pressure in any experiment because of temperature shock. On a large scale this is always hard to control.

2.2.2 Reply to Martijn Hoogeland

The committee did not uncover any corrosion or coating sensor reports. That is an area of interest, but it was not a focus of the work that we did. However, the committee for 2015 concentrated more on inspection methods and did report on some corrosion sensors at that time. We appreciate the input on the method mentioned, but cannot comment on its effectiveness.

One of the challenges of having owners or operators involved in the development of monitoring and prediction programs is that you have to actually install it on a platform that is operational to test it. And then you need to evaluate its effectiveness and show the business case. However, because you do not control the environment and other conditions rigorously, comparing it to a pilot study must be done so that people can see and trust that it is of use to them. Even so, if somebody has a very big scheme and they think they can collect a significant amount of data and show benefit on one platform or one ship, it then has to be transferable to another. Not being transferable could lead to it not being adopted on a wider scale. To avoid that, some abstraction, or some controlled scenario is needed in which you can test the concept to prove it, and then make it more generalised. This is definitely a challenge.

A great deal of inverse modelling has been done, but it is all very research-oriented. It has not really been applied into these more production processes. We are looking for such applications in which you can make use of sparse information to inform the rest of the system. That would be very handy, but it is an optimisation problem that has many outcomes, so trying to consolidate that is actually fairly hard, particularly in wave environments. We have not found any more practical demonstrations of inverse modelling, but we encourage it.

Thank you for mentioning a simple method of remote inspection. It is important to continue to update our understandings of new methods, that may be not purely robotic if you will, but are effective. Thank you.

2.2.3 Reply to George Wang

In the process of preparing the report and of differentiating between ship and offshore structures, we saw a definite difference in the adoptions of these technologies in those different regimes. Although not completely certain, we think that the economic benefit and the risk was clearer in the offshore, and operators were willing to do something more advanced. As those methods become more advanced, particularly with the class societies' involvement, they will start to transition to ships as people see the benefit.

The communication of the result of any analysis is very important. In the traditional deterministic manner, in which you have one factor of safety, and it seemed to work in the past, everything is fine. If you show that that number can vary, it makes people uncomfortable. Certainly, there are communities within the naval world that do not like to see risk because there is supposed to be no risk. But clearly there is always risk but there is no attempt to communicate specific risk measures, or probability of failure, because the assumption is no risk. Which is not true, but that is the assumption that some people make. So as soon as you add uncertainty to these things, people that are not familiar with, it causes a lock in the decision process.

I think we are all very comfortable with the probability relative to weather. But the probability of rain is not necessarily probability of a raindrop hitting you, but in your experience you understand what a probability of rain means. So, you have a mental map of that number to your experience. I do not think we have that same ability when it is probability of rupture or probability of failure of something else because it does not happen all the time (which would be horrible) and you do not have a reference by which to judge.

If you include uncertainty by saying that the probability of failure is 10^{-6} with a probability of accuracy of something else, it is sort of like 20 years ago, when the idea of fuzzy logic was getting overlaid on probabilistic methods. The whole fuzzy logic community in civil engineering tried to speak of the possibilistic versus the probabilistic. If people are already having trouble internalizing probabilistic, and then you throw possibilistic in there it leads to a lot of confusion. You just have to be careful about expectations and by paying attention to that in the communication. Trying to formulate the answer in light with how it is going to be used is essential.

2.2.4 Reply to Torgeir Moan

Thank you very much. We appreciate your comments. We think that the robustness as you describe in your life cycle strategy is an element. If you cannot see the crack you have to design for its being there. We do that now such as using fracture hardened steels, but there are elements of that in which we can do better. I had this dream early when I first came to work at the U.S. Navy Office of Naval Research of a simple solution after a professor suggested, "Put a sensor at the bow and the stern of the ship for a few years, and then we can say what is happening in between due to the vibrations." I said, "Well let's see." We then looked at a real data set and the damping kept changing depending on the fuel levels, and other things, so it was just useless. It was useless that it did not work, but it was useful that we learned that it did not work.

2.2.5 Reply to Mirek Kaminski

Thank you for that additional information.

2.2.6 Reply to Enrico Rizzuto

Thank you. One of the challenges is, and this is for the communication of uncertainty, there is also the communication of what is design life. I have been in discussions with people from the ship side, how long will this ship last? 30 years. Right? Just as a number, say 30 years. How much of that time is at sea? Oh, they do not know that. So now you have a disjunction, right there, it is not operating hours as in an aircraft, it is calendar time of a ship, which is meaningless. But we use that, and then an engineer makes an assumption and says 30%, 50% or 70% of that time is spent at sea, and that becomes an assumption of life. Then the assumption of wave encounters, which that feeds back to a fatigue analysis of a critical component, which has a chance of failing in 30 years. But that is not the life of the platform, that is not the same thing. There have been many discussions where the engineers say that this is the fatigue life. But for the owner it is not the same thing, necessarily unless they have an understanding that when it is economically unfeasible to maintain the structure, there is a completely different number. We can come up with something that allows us to get the job done, which is what we do today. Which is, we say the fatigue life given a certain operation, and that somehow maps to the expectation of design life and how to plan for it, but it is not quantitatively accurate. There is not really a definition of what that end of life is so that you can have that proportion. There is how long it is now, but there are other variables in there, and it would be very interesting to see how that can be portrayed without it being completely erroneous. This is an interesting point, but there are too many factors that start to come into play.

There is the technical answer, which tends to be of one component, or an assemblage of components, that they may have different risk levels. That is seen by the owner, or the decision maker, as to what they expect life to be. There is also the assumption that with periodic surveys you can just keep going if you look every five years and it is still fine then you just keep going. There are many very old ships out there and some seem perfectly fine, so it is a hard thing to put a clear number on, but we have to put a number on to do the design. But how that relates to the actual understanding of what that means is different, and I think we tend to be not as conservative as say aircraft, where the accumulated damage is 0.5, and a lot of the times we are higher than that, but the fatigue assessment for first failure in a platform is not the end. That is the point. Life is described in terms of operating time versus calendar time, and then there is the expectation for making a decision based on that information, which do not always line up.

Comment by Mirek Kaminski

I think it does not matter whether the ship is sailing 80%, 60% or even 40%, because the confidence of interval of 95% of S-N curve is factor of almost 7 or 8. So the predicted lifetime is either 1 or 8 years, so it means it is 20% or 100% at sea. This is what you are talking about.

2.2.7 Reply to Alysson Mondoro

We do not think that life-cycle costs are handled consistently. Some industries are able to plan further into the future, because the economics are more clear. In other industries the economics are less clear, and the upfront costs are hard to justify. It is not consistent across ships, and it is not necessarily consistent across offshore structures. It just really depends on who the customer is to allow for that. Certainly, from the U.S. Navy side it is a hard business case to make because it can seriously affect upfront business cost. And if you are adding material, say if you add 10% more material to your hull plate for some perceived benefit, whether it is potential for ice or whatever robustness you are looking for you then must look at the operating cost that is incurred. It is not just the upfront steel, it is the whole operating cost and the change in payload. It just has a huge ripple effect on the performance. This is a hard balance to do, and I think every industry sector does it a little differently. So, thank you.

2.2.8 Reply to Petar Georgiev

That would be very helpful information to have, but we did not search for that information.

Comment by Mirek Kaminski

It might be simple to find, because usually class societies give an additional class notation such as HULLMON class 1 or 3.

2.2.9 Response to Hyunkyoung Shin

The committee is not aware that fouling degrades structures. The only obstacle that we can think of is that the structure would have to be cleaned from time to time for the purpose of inspection and preservation. In such a situation, coatings that have an extremely long lifetime would be of value.

2.2.10 Response to Gaute Storhaug

This is a good question, because when all of a sudden you need to know how much longer a structure is going to last, the business case gets much easier to justify a monitoring system. But if you do not have the history, life extension decisions become more difficult to make.

The U.S. Coast Guard has developed the VALID project because in the past life extension decisions could only be rough estimates, and the admirals were tired of the answers. Now they are putting small monitoring systems on all of the ships from the beginning and they will keep the memory of that to allow for better decision-making in the future. In general, it is better to put the system in place up front. But then the question is, how small of a system can you use and still be effective. But up front is always better.

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